

## PLANS FOR EXPERIMENTS TO MEASURE $\theta_{13}$

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New experiments at accelerators and reactors are being designed to search for a possible non-zero value of the MNS matrix parameter  $\theta_{13}$ .

### 1. Neutrino Parameters and the MNS matrix

The neutrino mixing matrix, analogous to the CKM matrix for quarks, is the MNS matrix<sup>1</sup>. In the simplest case, that matrix can be parameterized by three angles and one CP violating phase. With the remarkable recent progress in understanding neutrinos, it is known that at least two of these mixing angles are large, unlike the angles in the quark sector. Despite these large angles, neutrino oscillation analyses are usually based on the assumption that there are only two neutrinos. This simplifies the analyses, and is accurate, but can be confusing.

The three mixing angles are designated  $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$ . Solar neutrino experiments and the KamLAND reactor experiment have measured  $\theta_{12}$ , also called  $\theta_{sol}$ . Atmospheric neutrino experiments have been used to measure  $\theta_{23}$  or  $\theta_{atm}$ . Long-baseline accelerator neutrino oscillation experiments have been designed to measure this angle. The third mixing angle,  $\theta_{13}$ , has only been limited to be smaller than  $\sin^2(2\theta_{13}) < 0.17$  by the CHOOZ<sup>2</sup> nuclear reactor experiment, at the currently favored value of  $\Delta m_{atm}^2$ . A CP violating phase which appears in the MNS matrix is called  $\delta$ . Long-baseline neutrino experiments would be sensitive to a non-zero value of  $\theta_{13}$  by measuring  $\nu_\mu \rightarrow \nu_e$  oscillations with a rate smaller than the dominant expected  $\nu_\mu \rightarrow \nu_\tau$  oscillations, so this is often called a sub-dominant process.

The current program of long-baseline neutrino experiments includes the K2K experiment in Japan, which has been running since 1998, the NuMI/MINOS program at Fermilab, which will start in 2005, and the CNGS program at CERN which is expected to start in 2006. Accelerator

beams consist mostly of muon neutrinos ( $\nu_\mu$ ) which are made when pions and Kaons decay. All three experiments expect to measure a change in the number and distribution of  $\nu_\mu$  as a result of  $\nu_\mu \rightarrow \nu_\tau$  oscillation. In addition, CNGS hopes to measure  $\nu_\tau$  appearance. These  $\nu_\tau$ s would be present in all three experiments, but the production of  $\tau$ s in K2K and MINOS is expected to be suppressed by kinematic thresholds.

## 2. The importance of $\theta_{13}$

I share the view that the single most important task before the neutrino community is to measure a non-zero value for  $\theta_{13}$  if it exists. While  $\sin^2(2\theta_{23})$  is near 1, SNO data supports that  $\sin^2(2\theta_{12})$  is approximately 0.7 and is clearly not maximal. Although we don't know what symmetries if any control the values of the MNS mixing angles, it is reasonable to expect that if  $\theta_{12}$  is not maximal,  $\theta_{13}$  is probably not exactly zero. The current limit on  $\sin^2(2\theta_{13})$  is  $< 0.17^2$ . Some of us suspect that a new search which is sensitive down to 0.02 would have a 90% chance of measuring a non-zero value for  $\theta_{13}$ !

Such a result would open up new possibilities for future neutrino research. If  $\theta_{13}$  is not zero, searches for matter effects and CP violation with accelerator neutrinos are feasible, in particular using  $\nu_\mu \rightarrow \nu_e$  measurements as described below in Equation 3. The observation of matter effects in  $\nu$  or  $\bar{\nu}$  tells us if  $\Delta m_{31}^2$  is positive (normal mass hierarchy) or negative (inverted mass hierarchy). Of even greater interest, the measurement of differences between  $\nu$  and  $\bar{\nu}$  oscillation parameters (after removing any matter effects) is sensitive to CP violating effects in the lepton sector. The measure of CP violation is the Jarlskog invariant, which is proportional to factors which include the product of all mixing angles and  $\Delta m^2$  values. With the large mixing in the lepton sector, CP violation in the neutrino sector is poised to be 50 times larger than in the quark sector, depending solely on whether  $\theta_{13}$  is near its current upper limit, or is much smaller.

The probability in vacuum for  $\nu_\mu \rightarrow \nu_e$  is<sup>3</sup>:

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 2 \sin(2\theta_{13}) s_{23} c_{13} s_{12} (s_{12} s_{23} s_{13} - c_{12} c_{23} c_\delta) \sin^2 \phi_{32} \\
 & + 2 \sin(2\theta_{13}) s_{23} c_{13} c_{12} (c_{12} s_{23} s_{13} + s_{12} c_{23} c_\delta) \sin^2 \phi_{31} \\
 & - 2 \sin(2\theta_{12}) c_{13}^2 [s_{12} c_{12} (s_{13}^2 s_{23}^2 - c_{23}^2) + s_{13} s_{23} c_{23} (s_{12}^2 - c_{12}^2) c_\delta] \sin^2 \phi_{21} \\
 & + \frac{1}{2} \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) c_{13} s_\delta [\sin \phi_{32} \cos \phi_{32} \\
 & - \sin \phi_{31} \cos \phi_{31} + \sin \phi_{21} \cos \phi_{21}]
 \end{aligned} \tag{1}$$

where  $\phi_{ij} = \Delta m_{ij}^2 L / (4E)$  and  $c_{ij}$  and  $s_{ij}$  refer to the cosine and sine of the mixing angle  $ij$ . The first two terms describe the behavior at an  $L/E$  corresponding to the large value of  $\Delta m^2$  and the terms proportional to  $\sin \delta$  ( $\cos \delta$ ) are CP odd (even).

In contrast reactor neutrino disappearance at small distances (i.e.  $L/E \sim \Delta m_{31}^2$ , so  $L \sim 1$  km), the formula is the simpler familiar one:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2(2\theta_{13})\sin^2\phi_{32} \quad (2)$$

### 3. Future Off-Axis Long-Baseline Neutrino Experiments

The search for a few percent  $\nu_\mu \rightarrow \nu_e$  in long-baseline experiments is made difficult by three backgrounds. First, there are  $\nu_e$  in the beam near the percent level from K and  $\mu$  decays in the beam pipe. Second, when the dominant  $\nu_\mu \rightarrow \nu_\tau$  oscillation takes place and a  $\tau$  is produced by charged current interaction, the  $\tau$  decays to an electron 17% of the time. Third, for any detector which resembles a calorimeter, some fraction of the neutral current events are going to be indistinguishable from an electron, particularly the single  $\pi^0$  neutral current events.

The kinematics of neutrino production is such that off the main axis of the neutrino beam, the average neutrino energy is both lower and more peaked toward a single value. The lower energy means that event rates are way down, already a significant limitation for long-baseline neutrino experiments. However, an off-axis narrow-band beam can be used to reduce all three backgrounds. The  $\nu_e$  in the beam are mostly at high energy, and do not constitute a large background to the expected signal. There are no  $\nu_\tau$  charged current interactions below 4 GeV, so the tau decay background is greatly reduced, and though the neutral current background is not eliminated, it is greatly reduced since there is no high energy tail on the neutrino spectrum. This has led to consideration of new accelerator based neutrino programs in the US and Japan.

#### 3.1. T2K

The Japanese Particle Research Center (JPARC) is a new 50 GeV proton synchrotron being built in Tokai. A neutrino beam is being planned.<sup>4</sup> In a first phase the accelerator would operate at 0.77 MW, but an upgrade to 4 MW is being considered. The 22.5 kiloton Super-Kamiokande detector is 295 km away, and the beam could be built to be simultaneously a few degrees off axis to that experiment and to the proposed site for a new 1000

kiloton Hyper-Kamiokande detector in Tochibora. With a 5 year run of JPARC, and the proposed 2 degree off-axis beam, T2K would be able to measure  $\theta_{13}$  or set a limit on  $\sin^2(2\theta_{13}) < 0.006$  at 90% CL for  $\delta = 0$ . The Hyper-Kamiokande detector would be similar in design to Super-K, using large 50 cm diameter Hamamatsu phototubes.

### 3.2. *NO $\nu$ A*

A proposal is being developed for an off-axis experiment using the NuMI beam at Fermilab.<sup>5</sup> Any detector would be built near the surface of the earth, about 10 km away from the center of the NuMI beam. The detector would have a mass of 50 Kilotons, and be sensitive to 1 GeV electron showers. The passive detector is planned to be 7 sheets of 2.5 cm particle board between readout planes. Active detector technologies being considered are resistive plate chambers and liquid and solid scintillator.

The liquid scintillator design is for 14.4 m long multi-cell extrusions of PVC, each containing 32 cells of width 3.75 cm. The cells would be 3 cm thick along the beam direction. A looped fiber would be inserted in each cell and an end-cap would be glued on one end, with a manifold/optical connector assembly at the other. There are no critical tolerances, such as positioning of the fiber. The proposal is under consideration at Fermilab.

### 3.3. *Brookhaven Wide Band Beam*

An alternative to the off-axis program has been developed at Brookhaven.<sup>6</sup> Using a wide-band beam, a huge detector such as the UNO described in the last section of this paper, and a longer distance to exploit possible matter effects, the Brookhaven idea uses fits to the full energy spectrum to find and measure oscillation parameters.

## 4. Reactor Experiments

From the discovery of the neutrinos by Reines and Cowan<sup>7</sup> at Savannah River to the evidence for  $\bar{\nu}_e$  disappearance at KamLAND<sup>8</sup>, reactor neutrino experiments have studied neutrinos in the same way – observation of inverse beta decay with scintillator detectors. Since the signal from a reactor falls with distance  $L$  as  $1/L^2$ , as detectors have moved further away from the reactors over the years, it has become more important to reduce backgrounds. That is achieved with a sufficient overburden, and experiments one kilometer or more away from reactors (Chooz, Palo Verde and KamLAND) have been underground.

The KamLAND experiment measured a 40% disappearance of  $\bar{\nu}_e$  presumably associated with the 2nd term in Equation 3:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong -\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) + 1 \quad (3)$$

The Chooz and Palo Verde data put a limit on  $\theta_{13}$  (through the first term in Equation 3) of  $\sin^2 2\theta_{13} < 0.17$ . Those experiments could not have had greatly improved sensitivity to  $\theta_{13}$  because of uncertainties related to knowledge of the flux of neutrinos from the reactors. They were designed to test whether the atmospheric neutrino anomaly might have been due to  $\nu_\mu \rightarrow \nu_e$  oscillations, and hence were searching for large mixing.

Any new experiment to look for non-zero values of  $\theta_{13}$  would need the following properties:

- two or more detectors to reduce uncertainties to the reactor flux
- identical detectors to reduce systematic errors
- carefully controlled energy calibration
- low backgrounds and/or reactor-off data

In Equation 3, the values of  $\theta_{12}$ ,  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$  are approximately known. In Figure 1, The probability of  $\bar{\nu}_e$  disappearance as a function of  $L/E$  is plotted with  $\theta_{13}$  assumed to be near its maximum allowed value. Note that CP violation does not affect a disappearance experiment, and that matter effects can be safely ignored in a reactor experiment. The large variation in  $P$  for  $L/E > 10$  km/MeV is the effect seen by KamLAND and solar  $\nu$  experiments. The much smaller deviations from unity for  $L/E < 1$  km/MeV are the goal for an accurate new reactor experiment.

The optimization of detector distances for such a new experiment is straightforward. The statistical power comes from measuring a deficit of  $\bar{\nu}_e$  (up to a few percent) at the far detector, along with a change in the energy spectrum consistent with that deficit. Depending on the value of  $\Delta m_{atm}^2$ , the far detector should be located about 1.7 km away. For higher statistics experiments, the importance of the shape of the spectrum is greater than the rate, and the optimum detector location moves about 30% closer. The optimum locations for detectors is thus sensitive to eventual systematic errors as well as oscillation parameters. But a near detector around 100m and a far detector around 1300 m will be near the optimum. Since the civil construction of laboratories might contribute half or more to the cost of an experiment, site conditions could change the optimization.

A list of possible sites for a new reactor experiment is included in Ta-

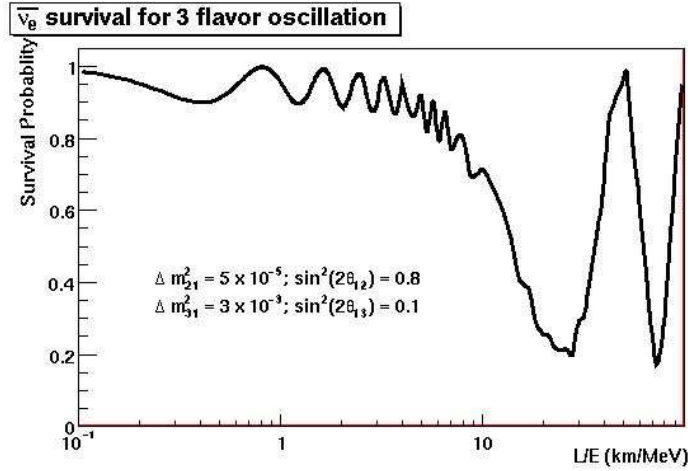


Figure 1. Probability of  $\bar{\nu}_e$  disappearance versus  $L/E$  for  $\theta_{13}$  near its current upper limit.

ble 4, along with a tabulation of previous reactor experiment sites.<sup>9</sup> One obvious choice is the site of the 7 GW CHOOZ reactors in France, and a proposal called “Double CHOOZ” is being prepared. A larger 15 ton far detector would be placed in an existing hall 1050 m from the two reactors, and new near detector would be placed close ( $\sim 200$ m). The existing site is an attraction, but is also a limitation. An even larger detector (50-1000 ton) would be desirable to achieve greater sensitivity on  $\theta_{13}$ . One of several projects being considered is to use the 7 GW Braidwood Reactors in Illinois, and place two shafts at 200 m and the other at 1800 m, on average from the two reactor cores. Two 25 ton detectors would be built.

A sensitivity of 0.02 in  $\sin^2 2\theta_{13}$  can be achieved with as little as 250 ton-Gigawatt-years, while an exposure of 8000 ton-Gigawatt-years may be required to achieve a sensitivity of 0.01.<sup>10</sup> A two or more detector reactor experiment can find a non-zero value for  $\theta_{13}$  faster and less expensively than an off-axis experiment. It does not face the degeneracies regarding CP parameters and the sign of  $\Delta m^2$ , and hence cannot address those issues. But a measurement of  $\theta_{13}$  by reactors followed by optimized off-axis experiments would together measure neutrino parameters with much less uncertainty due to degeneracies and correlations.

Reactor	Location	L	Power	Overburden	Mass
		m near/far	GW	MWE	ton
Previous Reactor Experiments					
Chooz	France	1100	8.5	300	5
Bugey	France	49/95	5.6	16	1/0.5
Palo Verde	Arizona	890	11.6	32	11.3
KamLAND	Japan	< 180 >	200 (26)	2700	1000
Possible sites for New Reactor $\nu$ Experiments					
Angra	Brazil	350/1350	4.0	60/600	50/50
Braidwood	Illinois	200/1800	7	250/250	25/50
Double CHOOZ	France	200/1050	7	50/300	10/10
Daya Bay	China	300/1500	11	200/1000	20/40
Diablo Canyon	California	400/1800	7	100/700	25/50
KASKA	Japan	350/1300	24	140/600	8/8
KR2DET	Russia	115/1000	1.5	600/600	45/45

## 5. UNO nucleon decay project

One of the reasons for the tremendous progress in understanding the neutrino has been the fact that several detectors were built underground to search for nucleon decay. The UNO detector<sup>11</sup> is proposed as a next generation underground water Cerenkov detector that probes nucleon decay beyond the sensitivities of the highly successful Super-Kamiokande detector.<sup>11</sup> The baseline conceptual design of the detector calls for a “Multi-Cubical” design with outer dimensions of 60x60x180 m<sup>3</sup>. The detector has three optically independent cubical compartments with corresponding photo-cathode coverage of 10%, 40%, and 10%, respectively. The total (fiducial) mass of the detector is 650 (440) kton, which is about 13 (20) times larger than the Super-K detector. Water Cerenkov technology is the only realistic detector technology available today to allow a search for this decay mode for proton lifetimes up to 10<sup>35</sup> years. UNO provides other opportunities, such as the ability to observe oscillatory behavior and appearance in the atmospheric neutrinos; precision measurement of temporal changes in the solar neutrino fluxes; supernovae and supernova relic neutrinos; and searches for astrophysical point sources of neutrinos. UNO is an ideal distant detector for a long-baseline neutrino oscillation experiment with neutrino beam energies below about 10 GeV, as envisaged by the Brookhaven working group.

## 6. APS Neutrino Study

A large number of ideas to study the neutrino sector are being pursued, and they come with a variety of costs and feasibility. Ideas for “neutrino factories” to study  $\theta_{13}$  are now considered part of the program of the far future. A study in the United States to put the differing ideas for neutrino experiments into a single coherent program is being developed under the auspices of four divisions of the American Physical Society. Six working groups are holding meetings and a report is due in the late summer of 2004. Reactor experiments to see if  $\theta_{13}$  is non-zero, followed by accelerator projects to measure CP effects if it is, should be a major part of such a program.

### References

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